While one of the major uses of such capability is single frequency network, it can be used for robust reception of ATV transmission. For example, COFDM may allow the use of whip or rabbit ear antennae in major metropolitan areas, Also consumers may not have to adjust the direction of outdoor antennas for each channel even if ATV transmitters are not co-located. The value of such robustness deserves further study.

Impulse Noise

COFDM technology claims to have excellent immunity towards impulse noise. Its multiple carrier structure allows significant flexibility in spectral shaping. Sophisticated channel coding such as multiple carrier redundancy and time multiplexing help to avoid data loss. These techniques along with other signal processing techniques, such as the application of a Fast Fourier Transform at the receiving end provide an impulse noise immunity advantage of about 10 dB according to CCETT, when compared to single carrier digital transmission systems. It is not known what single-carrier system implementation was used and whether interleaving was used in the comparison. Thus, impulse noise interfering with a received COFDM signal is evenly distributed across the many carriers of the system in the frequency domain. Since the power of the interfering impulse noise signal is averaged, there is less chance for channel errors.

Frequency Re-use / Single Frequency Networks

COFDM may permit better service to homes through use of on-channel repeaters and indoor reception. The ability to withstand a 0 dB ghost, as might be encountered with on-channel repeaters and an omni-directional receive antenna was demonstrated to the FCC Advisory Committee delegation by CCETT. In this sense, COFDM uses spectrum more efficiently, thus avoiding the need for off-frequency translators.

COFDM may permit broadcasters to have more flexibility in shaping service areas. The future prototype hardware being developed by HD-DIVINE and NTL both incorporate the ability to change the amplitude, constellation density and other COFDM parameters on a carrier-by-carrier basis.

The COFDM transmission techniques attempt to take advantage of all transmission paths. To avoid intersymbol interference due to ghosts, a guard interval is used before each symbol time, thus extending the time between successive symbols. To allow frequency reuse within the normal service area of a broadcast transmitter, the COFDM signal transmitted uses the guard interval between symbols to avoid intersymbol from nearby co-channel transmitters. However, since the guard interval extends the symbol time, the net result is a reduction of the net delivered data rate.

A true Single Frequency Network (SFN) would use a lattice of synchronized on-channel transmitters. Frequency planners for Europe seem to be heading in that direction to cover an entire country with one television program using only one frequency. The approach the US. would probably use would be to use on-channel secondary low power transmitters to re-broadcast the same program in areas not adequately served by a single primary high power transmitter. Note that a SFN requires the same program material be transmitted at <u>all</u> times.

Currently, US. broadcasters use broadcast translators, utilizing a different channel for retransmission for coverage fill-in. The main difference of the SFN approach is that the on-channel repeaters could be synchronized to the same signal source, but they don't necessarily have to be synchronized. The transmitting repeaters could obtain their signal source from over-the-air pickup and utilize omni-directional transmit antennas. In order for the receive antennas to be omni-directional, the transmitter spacing must be set up properly as well as the COFDM guard intervals. Proper adjustment of the delay can further improve coverage. If synchronization is to be used, the signal has to be delivered to the secondary transmitters through use of an optical fiber, microwave link or satellite circuit. In that case the coverage can be further improved by use of "negative delays," relative to the propagation delays from the main transmitter path and positive delays, using memory at the repeater to further delay the off-air signal.

Co-channel Protection in a Single Frequency Network (SFN) Environment

A characteristic of COFDM is that, through use of on-channel repeaters, the coverage area can be shaped to reduce the power requirements, reach precise audiences and produce a good resolution signal roll-off at the coverage edge. The result is reduction in the separation distance between an adjacent co-channel coverage area, thereby increasing the overall spectrum efficiency. This shaping can help to resolve severe cases of co-channel interference. The number of needed repeaters is the limiting factor of the separation distance. The more on-channel repeaters used, the sharper the signal strength roll-off.

Adaptation to North American Environment

All of the systems we discussed and saw demonstrated were designed to European standards of 8 MHz channels. All assumed a single-frequency network design, with its concomitant emphasis on multipath immunity. Temporal guard intervals could be specified exactly in the design, since they were determined by the spacing between transmitters in the single-frequency network. Twice during our visits (once at LER and once at CCETT) the point was made that recent studies of wide-area Single Frequency Networks for Europe have shown that the COFDM demodulator would have to deal with strong echoes of 100 microseconds or more. A COFDM design for 6 MHz channels which attempts to provide approximately 19 Mb/s data rate with 100 microseconds or greater guard interval will require the use of thousands of active carriers (the HD-DIVINE strawman design for 6 MHz channels envisions the use of some 5500 active carriers, with a guard time of only 32 us). Such a design will lead to an extremely stringent phase noise requirement (well beyond what can be provided by consumer-grade tuners, we believe), as discussed further in other sections of this report. We recognize that there are other implementation scenarios under which echoes would be shorter, but we wish to inject a note of caution that some Single Frequency Network scenarios may be impractical to support with a reasonable COFDM parameter set.

There are today no hardware and no well-considered proposals for North American COFDM transmission. We feel we should make some estimate of the magnitude of the task if we were to undertake creation of a COFDM system for North America. We emphasize that the task is a complete system design, not just creation of hardware. We can benefit from European experience, but the system compromises for North America will be unique and are not now known.

Tasks:

A first task is establishment of a multipath maximum delay time design goal. This determines the guard interval and eventually the number of carriers. (The carrier bandwidths must be narrow enough, with long enough symbol times, that the guard interval will be a reasonably small fraction of the symbol time; otherwise, the efficiency of the channel decreases unacceptably. Specifying the guard interval does not determine the maximum ghosting delay that can be effectively handled; it does set the limit on the maximum 0 dB level ghost that can be eliminated - longer ghosts can be handled at lower amplitude levels as noise.) We have avoided formalizing this specification for the current North American proposals, because equalizer performance is not such a central part of the overall system design in these proposals - for single carrier systems with conventional equalizers, the time duration can be extended or shortened in the hardware without impacting other portions of the design or the algorithms.

Once agreement is reached on the multipath design goal, all the rest of the system parameters must be determined. A key issue after the number of carriers is the trellis coding. Extensive and protective trellis coding may reduce the payload data rate. The cure for this is more dense constellations (e.g., 64- or 128- or 256-state QAM), which increase (i.e., penalize) the threshold S/N required. The anticipated impact on coverage must be analyzed.

A system for acquisition, tracking, and multipath characterization must also be designed. Various combinations of pilot tones and training signals have been proposed in Europe. We will need to improve on this work if we are to achieve the level of practicality we have demanded of the current North American systems. Another unsolved problem is handling of practical levels of phase noise from consumer tuners and expected cable systems. We emphasize that these tasks require invention, not "simply" optimization of known parameters.

We believe that, if hardware is constructed, it should have flexibility to permit experimentation. Computer simulation, accompanied by experimentation on this flexible hardware, will allow refinement of the system. We will not address in this report how and under what supervision hardware might be constructed.

The effects of the relatively high peak-to-average power ratio of COFDM must be better documented and analyzed from both transmitter design and coverage / interference standpoints.

Time Estimate:

We believe that the above process, from beginning of the specification phase through optimization of the flexible hardware, would require about 9-15 months, depending on a consensus within the industry and commitment of funding. At that point, a COFDM system could be in a state of readiness for testing comparable to the state of the QAM and VSB proposals today, with the probable exception of the tuning system.

COFDM Field Testing Status

Summary of Field Testing Status

Early field testing of COFDM prototype hardware by various European investigators has played and will continue to play a significant role in the development and evaluation of COFDM transmission. Unlike in the United States, Europe did not confine its field testing activities to the verification of the ATV prototype hardware in the field and the validation of the laboratory test results, but rather to assist them in the development and refinement of the COFDM system parameters and the ultimate selection of a COFDM system.

All three systems visited by the Task Force conducted field measurement trials or demonstrations with either their current or an earlier version of their prototype equipment. All three proponents plan to conduct additional and more comprehensive field tests in the 1994-1995 time frame. Moreover, the Task Force was informed that other members of the European Project on Digital Video Broadcasting (ER-DVB) have conducted or plan to conduct additional field testing during the same time period.

Although the level and extent of field investigations varied among the various system proponents we visited, the Task Force is of the opinion that the amount of field test data on digital transmission -- especially relating to multipath -- collected to date in Europe is far greater than what is known to be available in the United States. The European data could be useful in gaining a better understanding of multipath propagation in general and better characterization of the ATV transmission channel.

Background

The greatest strength of COFDM is in its claimed capability of providing excellent performance in a multi path environment and its ruggedness to different types of interference. While these claims can be investigated and/or verified in the laboratory, most European investigators believe that field testing is an essential part of investigating the multipath performance of COFDM. This belief is further reinforced by the need to carefully engineer these new digital systems within the existing bands since the overall spectrum availability for digital television in Europe is much more limited and far more complex than in the United States. Moreover, their desire to offer indoor and mobile reception and to implement national Single Frequency Networks (SFNs) demand more extensive field investigations than may be needed in the United States.

For the past two years or so, a number of OFDM/COFDM field measurement programs were conducting through Europe. These measurement programs ranged from a cursory look-and-see to a more comprehensive evaluation of OFDM/COFDM under real-world multipath conditions. Below is a brief description of some of these measurement programs.

Status

HD-DIVINE

Since the demonstration of an initial prototype in June 1992 at IBC, HD-Divine has been demonstrating their system (version 1.0) at various trade shows throughout Europe. The version 1.0 equipment was installed on two mobile trailers capable of transmitting and receiving the COFDM signal at very close distances (a few feet to a 1.2 mile away).

Limited field trials were conducted in the city of Stockholm using the version 1.0 hardware. The field tests were conducted using an existing UHF-PAL transmitting facility (approximately 1000 feet above ground) and operating at 44 dB below its rated analog transmitted power. Using a receiving installation at the standard 30 feet above ground, measurements and subjective observations were carried out a different locations within a 10 km radius from the transmitter. The HD-Divine decoder did not incorporate forward error correction. Even though the decoder did not include forward error correction, good reception was achieved within a 10 km radius of the transmitter.

HD-Divine plans to conduct more extensive field testing with their new hardware (version 2.0) in the 1995 time frame.

CCETT

The CCETT prototype hardware was originally demonstrated a the Montreux International Television Symposium in June 1993. The prototype hardware used at the Montreux Symposium was not the same as the one shown to the Task Force at Rennes, but the earlier version (448 carriers and 16 QAM). The Montreux demonstration used a transmitting facility located approximately 10 miles from the receiving installation. The receiving installation was located on the second level of a four-story building. An indoor vertical whip antenna was used to receive the COFDM signal.

No other field test measurement programs were reported by CCETT, however plans are underway to conduct extensive field tests in the 1994 time frame.

Thomson CSF LER

The Thomson prototype hardware was originally demonstrated in June' 1993 at Montreux. The Montreux demonstration used a dual polarization transmission/reception configuration and transmitted one HDTV and four SDTV channel on the same 8 MHz channel. The transmitting facility was located approximately 1/2 mile from the receiving installation.

Since the Montreux demonstration, Thomson in collaboration with BBC conducted a moderately large field test experiment in the United Kingdom. Specifically, the prototype was used to test the robustness of OFDM in the field in the presence of low-level and strong echoes or PAL interference. Approximately 60 receiving locations in and around the transmitting facility and as far out as 25 km from the transmitter were surveyed. BER data and other observations were recorded on both polarizations. The measurements were conducted at 30 feet above ground using two separate highly directional antennas. Except for a limited number of locations where the cross-polarizations discrimination was 3 dB or less, dual reception was achieved using separate antennas. A graph of field strength versus bit error rate is shown in Figure 3 of with this report.. The hardware used for this measurement program did not include an efficient error-correction mechanism or suitable guard band (less than 8 microseconds) to deal with strong and/or large delays echoes.

Thomson plans to conduct more extensive tests in the 1994-1995 time frame.

NTL / ITC

By far the most extensive field measurements conducted to date in Europe was undertaken by NTL/ITC. Since its inception, the SPECTRE investigators have and are expected to rely heavily on field observations to assist them in the design and optimization of their channel coder/decoder. Specifically, the SPECTRE project conducted a number of large-scale field experiments using OFDM transmission and a number of different modulation schemes (QPSK, 8PSK and 16 QAM) over an 18 month period. The experiments were generally undertaken to collect propagation data and catalog different multipath conditions so as to better characterize and/or model the transmission channel. Most of the field measurements were conducted in the southwestern part of England.

While most of the experimental data is currently being analyzed and has not been released, NTL/ITC reported extensively on one of its field measurement programs intended to collect bit error rate measurements over a wide geographical area. Approximately 300 receiving locations within a 30 mile radius of an OFDM transmitter located at Stockland Hill were measured along with measurements relating to interference from and to existing co-channel and adjacent channel PAL transmitters. In addition, information was collected on the effect of ignition and impulse noise on an OFDM signal in the field. A standard 30 foot receiving installation was used for this experiment.

In addition to the field measurement program underway, NTL has also conducted two live demonstrations within the United Kingdom in 1992. The first demonstration was held at Exeter in South-West England and the second in London. The system used QPSK modulation of an OFDM signal at an ERP of 50 Watts. The net video data rate was 10 Mbit/s.

NTL plans for additional and more extensive field measurements in 1994.

Recommendation

During our visits, subsequent discussions, the questions and answers that preceded the visits, and the preparation of this report, we have considered COFDM very seriously. We offer no clear-cut and obvious recommendation. We believe that COFDM technology is a potential modulation technique for North American ATV, but that it will require considerable additional development. We have determined that no COFDM hardware to North American specifications exists in a state ready for testing, and we have learned that there are no plans to create such hardware in Europe. We have identified two important "gating" decisions that should <u>precede</u> any effort to create a COFDM system for North America:

1) Before undertaking the development of a COFDM system for North America, we should determine that COFDM's claimed strong tolerance of multiple ghosts is a compelling advantage for terrestrial broadcast in North America; we must also establish that the somewhat lesser ability of QAM and VSB systems with multiple ghosts represents an important practical handicap in terrestrial broadcast. We must recognize that no solution for handling multipath associated with mobile reception exists for COFDM at ATV data rates.

2) Before ACATS embarks on a development program, it must recognize that development of a COFDM system for North America will delay the ATV process; ACATS must determine that delay is acceptable. A COFDM system requires inventions to create practical receiver

circuits, signal acquisition times, synchronization, and carrier recovery. The system parameters must also be defined by experiment.

The people with whom we met on this trip were not appropriate for discussions of licensing policies, nor were the members of our delegation. A separate discussion of licensing policy should be undertaken. We believe that we must obtain the promise of a non-discriminatory policy with "fair and reasonable" rates.

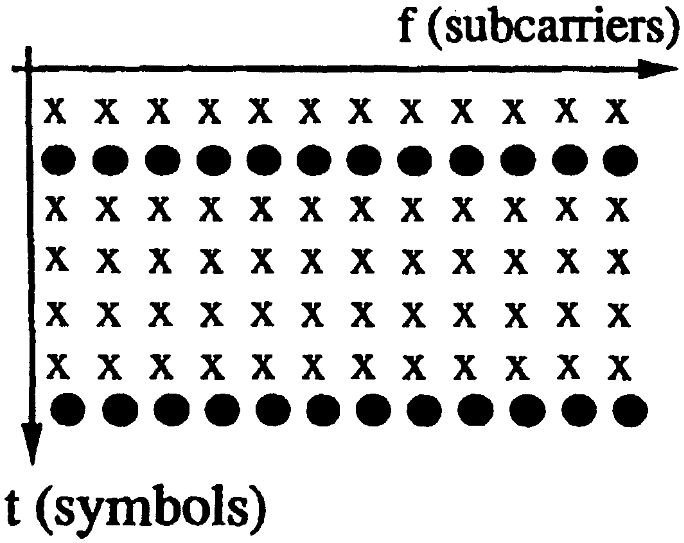
We recommend that we continue to monitor COFDM developments worldwide. If the Advisory Committee considers the matter important, this Task Force would undertake the paper design of a COFDM system for North America; we would consult with our colleagues in Europe and Japan in the process. The contacts we have made on this trip have all indicated they would be happy to share their experiences to help us with such an undertaking.

	DIVINE 1.0	DIVINE 2.0	LER	CCETT Prototype	NTL	DIVINE Strawman	CCETT Strawman
FFT Size (Points)	1024			1024	1024	8192	2048
Number of Active Carriers	448	<= 13 K (?)	481	840/896	432	5500	1386/1408
Carrier Spacing (kHz)	15.625					1	
Bandwidth (MHz)	7.76/8.0	flexible	7.07	7	7.47	5.5	5.5
Omitted Carriers: PAL Luma			35				
Omitted Carriers: PAL Chroma			12				
Omitted Carriers: PAL Sound			18				
Modulation per Carrier	16 QAM	4-256 QAM	256 QAM	64 QAM	QPSK/8PSK 16 QAM	64 QAM	64 QAM
Gross Bit Rate w/FEC Overhead (Mb/s)	27.017			20.58	13.5 (QPSK)		19.096
Net Usable Bit Rate (Mb/s)	25.088	<= 35	34.01/29.7			19.03	
Total Symbol Duration (us)	65.95/64.0			160		1032	288
Length of Guard Interval (us)	0/1.95	20 or more	8.8	32	0/2	32	32
Active Symbol Duration (us)	64		70.4	128	64		256
Transmission Frame Time (ms)				24		43.344	72
Total OFDM Symbols/Frame	512						250
Number of Sync Symbols/Frame	3	<= 3		3		2 Test + 40 Data	2 + 1/64 of Carriers
Channel Equalization Overhead			1/15 symbols				
Active OFDM Symbols/Frame	509	flexible					248
Eb/No @ 10**(-6) (Gauss Channel)						8.3 dB	
C/N Threshold (dB)		18	22-23				
Inner Code		Trellis	Trellis	Trellis		Trellis	Trellis
Inner Interleaving						Frequency	
Outer Code	RS(224,208)	RS	RS		RS(255,239)	RS(255,239)	
Outer Interleaving						Time	
Carrier Acquisition Range (kHz)	+/- 10-20		12 (+/- 6 ?)				

Table 1 - Summary of OFDM Systems

CHANNEL ESTIMATION

time interpolation:
reference symbols



frequency interpolation:
pilot subcarriers

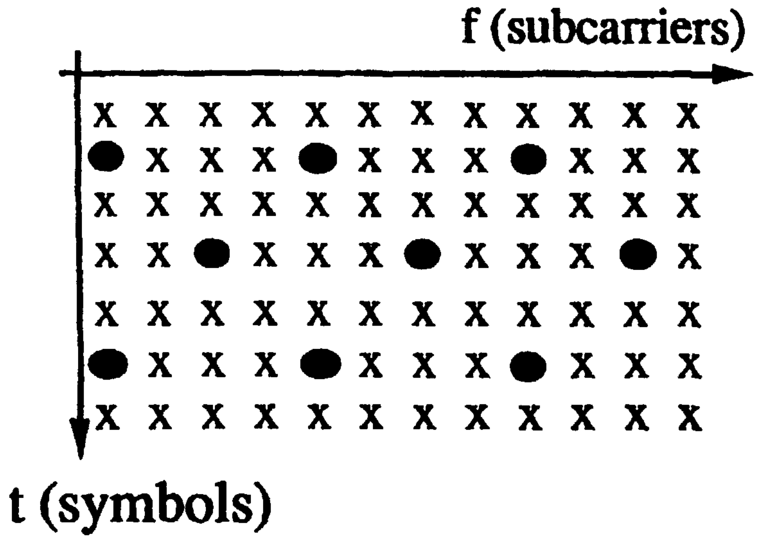


Figure 1

[redacted]

COHERENT DEMODULATION

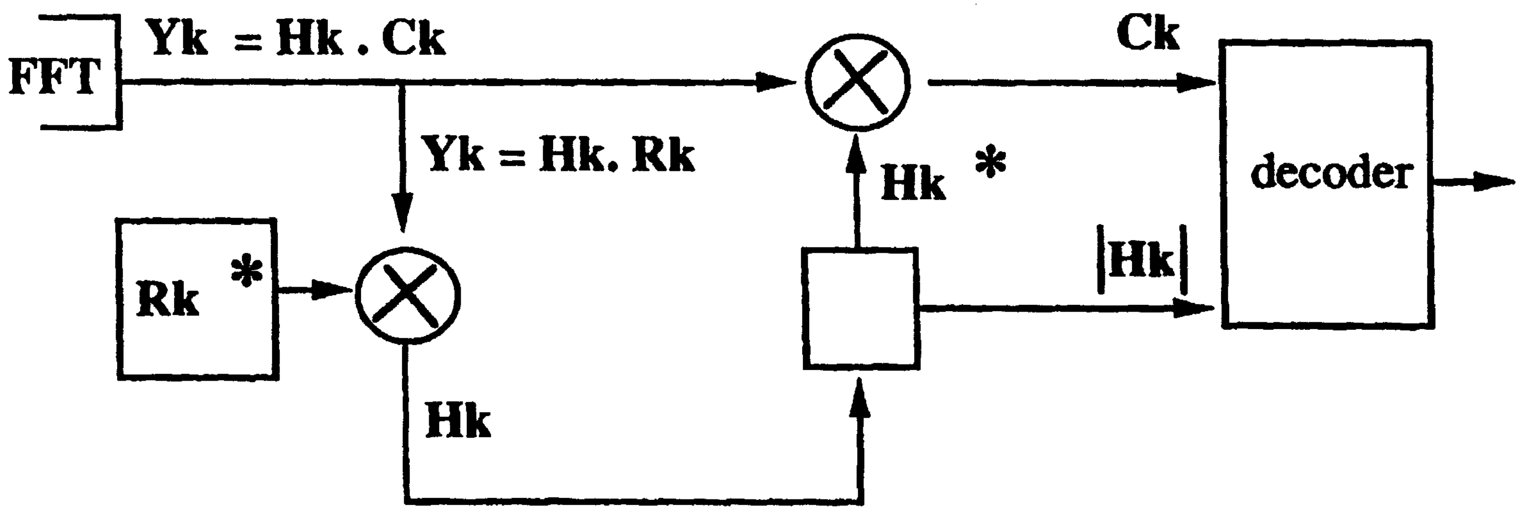
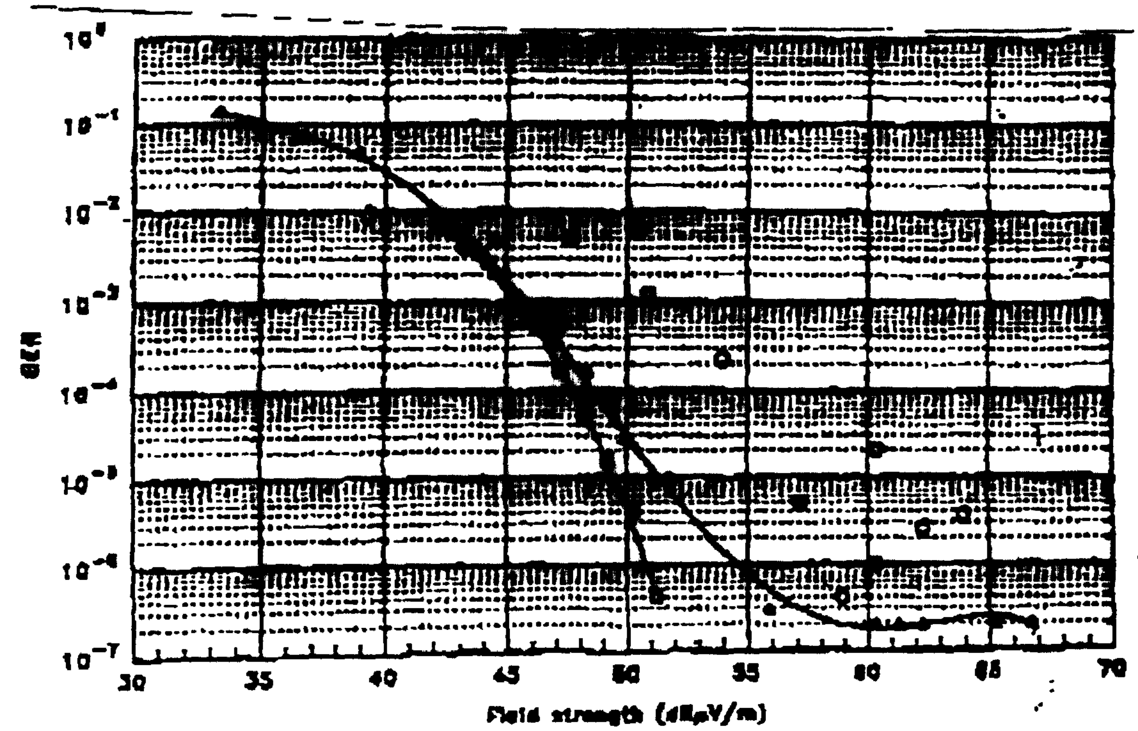


Figure 2



□ Lab measurements

▲ Field measurements-low level echoes, no PAL interference

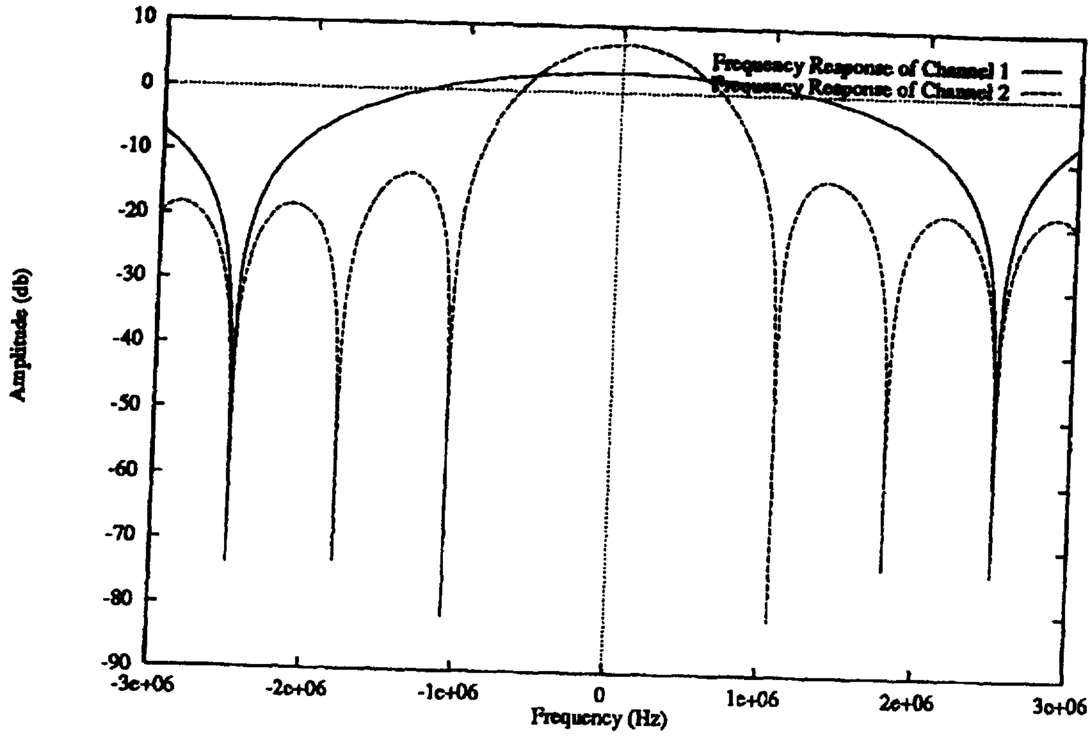
○ Field measurements-strong echoes or PAL interference

Figure 3

APPENDIX:

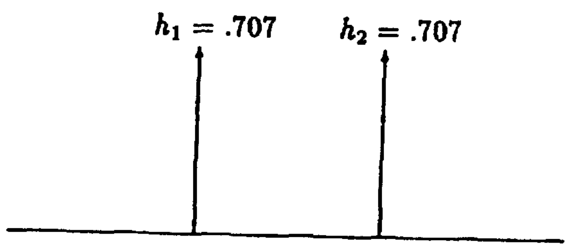
While COFDM exhibits performance enhancement in some multipath channels, it should be noted that it is not possible to extrapolate the results from a few examples to all cases. CCETT mentions that the "worst case" channel is a 2-ray multipath with a 0 dB echo and that adding echoes will improve C/N without any performance degradation. This claim cannot be theoretically proven and in fact it can be shown in many cases that the addition of extra echoes causes a greater loss in performance. For example, Figure 1 shows the impulse responses of 2 channels: Channel 1 is a single echo channel with a 0 dB echo and Channel 2 is the impulse response of a channel with a 0 dB echo and additional echoes. In both cases the echoes are spaced equidistant from each other. Figure 2 shows the frequency response of these two channels and it is clear that Channel 2 exhibits more nulls and will have a worse performance in terms of BER than Channel 1, even though both channels have been normalized to have the same energy. In fact, if the echo spacing is equal to the symbol rate, for Channel 2 the loss with optimal maximum likelihood sequence estimation is of the order of 7 dB (see Digital Communications by Proakis, page 624) while for Channel 1 the theoretical loss is very close to zero. While this comparison is based on an optimal receiver and other ideal conditions, it does show that it is misleading at best to say that the single 0 dB echo channel is the "worst case" channel.

Another point to note is that the performance of COFDM in multipath depends very heavily on the coding and hence a much lower code rate (2/3 as opposed to 4/5 for single-carrier systems) and more complex coding is required.

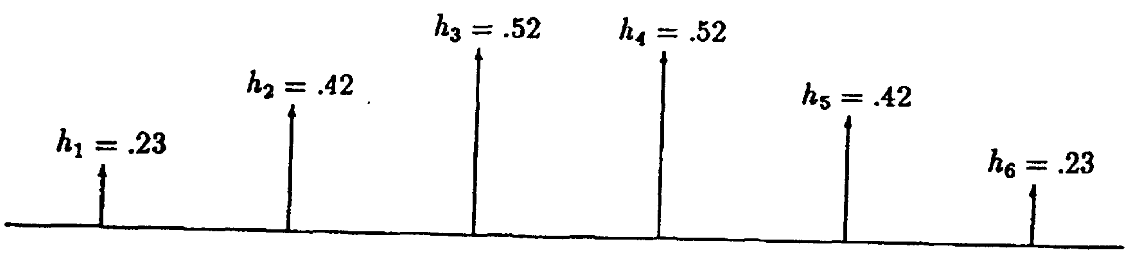


Frequency responses of Channel 1 and Channel 2

Figure A-1



(a) Impulse response of Channel 1.



(b) Impulse response of Channel 2.

Impulse response of two multipath channels

Figure A-2